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Abstract

[1] Satellite monitoring of changes in terrestrial water storage provides invaluable information regarding the basin-scale dynamics of hydrological systems where ground-based records are limited. In the Bengal Basin of Bangladesh, we test the ability of satellite measurements under the Gravity Recovery and Climate Experiment (GRACE) to trace both the seasonality and trend in groundwater storage associated with intensive groundwater abstraction for dry-season irrigation and wet-season (monsoonal) recharge. We show that GRACE (CSR, GRGS) datasets of recent (2003 to 2007) groundwater storage changes (ΔGWS) correlate well (r=0.77 to 0.93, p-value <0.0001) with *in situ* borehole records from a network of 236 monitoring stations and account for 44% of the total variation in terrestrial water storage (ΔTWS); highest correlation (r=0.93, p-value <0.0001) and lowest root mean square error (<4 cm) are realized using a spherical harmonic product of CSR. Changes in surface water storage estimated from a network of 298 river gauging stations and soil-moisture derived from Land Surface Models explain 22% and 33% of ΔTWS respectively.

Groundwater depletion estimated from borehole hydrographs (−0.52±0.30 km^3/yr) is within the range of satellite-derived estimates (−0.44 to −2.04 km^3/yr) that result from uncertainty associated with the simulation of soil moisture (CLM, NOAH, VIC) and GRACE signal-processing techniques. Recent (2003 to 2007) estimates of groundwater depletion are substantially greater than long-term (1985 to 2007) mean (−0.21±0.03 km^3/yr) and are explained primarily by substantial increases in groundwater abstraction for the dry-season irrigation and public water supplies over the last two decades.

1. Introduction

[2] Groundwater is the world's largest distributed store of freshwater [*Shiklomanov and Rodda*, 2003]. Quantification of changes in groundwater storage (ΔGWS) is consequently critical to understanding terrestrial freshwater dynamics and assessing the impacts of groundwater withdrawals as well as climate variability and change[*Yeh and Famiglietti*, 2009]. Reductions in groundwater storage, referred to as "groundwater depletion", have recently been detected in arid and semi-arid areas where intensive groundwater abstraction sustains irrigated agriculture [*Konikow and Kendy*, 2005; *McGuire*, 2007; *Leblanc et al.*, 2009; *Rodell et al.*, 2009; *Famiglietti et al.*, 2011]. The magnitude of groundwater depletion is such that it is estimated to account for up to 25% of recently observed rises in global sea levels [*Wada et al.*, 2010]. There is, however, no global reporting of *in situ* groundwater observations to monitor ΔGWS [*Rodell and Famiglietti*, 2001; *Taylor et al.*, 2010].

[3] The Gravity Recovery and Climate Experiment (GRACE) [*Tapley et al.*, 2004] offers the opportunity to monitor monthly changes in total terrestrial water storage (ΔTWS) via satellite observations at regional scales starting from April 2002 [*Cazenave and Chen*, 2010]. ΔGWS is estimated from GRACE-derived ΔTWS after deducting the contribution of changes

in remaining terrestrial water stores including soil moisture (ΔSMS), surface water (ΔSWS), and ice and snow (ΔISS) over a particular time period (t) (equation 1).

$$\Delta GWS_t = \Delta TWS_t - \Delta SMS_t - \Delta SWS_t - \Delta ISS_t \qquad (1)$$

[4] Accurate disaggregation of GRACE ΔTWS into different water stores is therefore critical to quantifying ΔGWS. Recent studies in humid environments [*Frappart et al.*, 2008; *Han et al.*, 2009; *Kim et al.*, 2009; *Frappart et al.*, 2011] highlight the substantial contribution (>25%) of ΔSWS to ΔTWS. Robust estimates of ΔGWS have been resolved from GRACE ΔTWS in the USA where these satellite data are validated using ground-based (*in situ*) hydrological datasets [*Swenson et al.*, 2006; *Yeh et al.*, 2006; *Rodell et al.*, 2007; *Strassberg et al.*, 2007]. Several studies have sought to quantify changes in terrestrial water stores in the humid tropics [*Crowley et al.*, 2006; *Winsemius et al.*, 2006; *Tiwari et al.*, 2009] but none of these is well constrained by ground-based observations.

[5] GRACE measurements record large-scale variations in ΔTWS. The application of GRACE measurements to space-limited areas (e.g. river basin) is associated with both bias (i.e. amplitude damping from mass inside the basin) and leakage (i.e. sensitivity to masses outside the basin) [*Chambers*, 2006; *Swenson and Wahr*, 2006; *Klees et al.*, 2007; *Longuevergne et al.*, 2010]. Multiplicative [*Swenson and Wahr*, 2006] and additive [*Klees et al.*, 2007] approaches to account for bias and leakage have been developed using a priori information on terrestrial distributions in water stores derived from Land-Surface Models (LSMs). Such data-processing methods for GRACE data are critical when the basin area (Bengal Basin ~138,000 km^2) marginally exceeds the limits in the resolution (~100,000 km^2) of GRACE observations [*Longuevergne et al.*, 2010].

[6] The Bengal Basin of Bangladesh and West Bengal (India) (Figure 1), the largest river delta in the world [*Shamsudduha and Uddin*, 2007], is an ideal location to test the robustness of GRACE-derived estimates of ΔGWS in the humid tropics for four reasons. First, the basin

features dense networks of ground-based, surface-water and groundwater level monitoring stations with which to resolve and test estimates of ΔGWS from ΔTWS [*Shamsudduha et al.*, 2009; *Steckler et al.*, 2010]. Second, a basin-wide database of storage coefficients, derived from 279 pumping-test records [*BWDB*, 1994; *Shamsudduha et al.*, 2011], enables conversion of groundwater-level observations to ΔGWS. Third, substantial intra-annual (seasonal) and inter-annual changes in groundwater storage (see supplementary Figures S1 and S2 for dry and wet-season groundwater levels in Bangladesh) occur as a result of intensive groundwater abstraction for dry-season irrigation and wet-season (monsoonal) recharge [*Shamsudduha et al.*, 2011]. Fourth, the basin's area in Bangladesh (~138,000 km^2) is around the limit in the resolution of GRACE observations. In addition, the Bengal Basin provides a representative case study for other Asian Mega-Deltas for which detailed ground-based monitoring records are unavailable.

[7] Here, we test the ability of GRACE satellite measurements to trace intra-annual (seasonal) and inter-annual ΔGWS in a highly seasonal, tropical humid hydrological system, the Bengal Basin, over the period of January 2003 to December 2007 using *in situ* (ground-based) observations of groundwater levels [*Shamsudduha et al.*, 2009] and distributed specific yield estimates [*Shamsudduha et al.*, 2011]. Critically, we resolve contributions of ΔSWS and ΔSMS to ΔTWS using *in situ* observations of ΔSWS from a network of 298 river-level monitoring stations across Bangladesh [*Steckler et al.*, 2010] and simulations of ΔSMS from three Land Surface Models (LSMs) (CLM, NOAH, VIC) provided by the Global Land Data Assimilation System (GLDAS) [*Rodell et al.*, 2004]. Further, we evaluate the robustness of different GRACE data-processing methods for resolving ΔGWS in a highly seasonal, tropical humid basin where variations in the dry and wet-season groundwater levels are substantial (mean annual amplitude 5.4±2.6 m). Finally, we place estimates of recent (2003 to

2007) trends in ΔGWS in the context of long-term trends (1985 to 2007) derived from long-term *in situ* observations.

2. Datasets and Methods

2.1. GRACE datasets

[8] In this study, we use both post-processed gridded GRACE datasets and spherical harmonic (SH) products, provided by the Centre for Space Research (CSR) and Groupe de Recherche en Géodesie Spatiale (GRGS), to derive ΔGWS in the Bengal Basin. Gridded files include: (i) a monthly, 1°×1° CSR GRACE time-series dataset masked over the Bengal Basin in Bangladesh (land grid version "ss201008"; http://grace.jpl.nasa.gov/data/; hereafter referred to as CSR GRID) [*Swenson and Wahr*, 2006] wherein bias and leakage are compensated using a scaling factor to restore GRACE TWS signal amplitude for each grid; and (ii) a 10-day, 1°×1° GRGS GRACE time-series data (version RL02; http://grgs.omp.obs-mip.fr; hereafter referred to as GRGS GRID) [*Lemoine et al.*, 2007; *Bruinsma et al.*, 2010]; no scaling factor is applied for the GRGS GRID data. The scaling coefficients provided for each 1° bin of the CSR GRID data are intended to restore much of the energy removed by destriping, filtering, and truncation processes [*Swenson and Wahr*, 2006]. Unlike CSR GRID monthly data, GRGS GRID products do not require additional filtering [*Biancale et al.*, 2006; *Lemoine et al.*, 2007; *Ramillien et al.*, 2008; *Tregoning et al.*, 2008; *Bruinsma et al.*, 2010]. SH-based products (hereafter referred to as CSR SH for CSR and GRGS SH for GRGS products) are processed based on methods described by *Longuevergne et al.* [2010]. Bias and leakage are calculated using the additive hypothesis of *Klees et al.* [2007]. In the Bengal Basin, GRACE error amounts to 5 cm and is estimated by computing variability in the oceans at the same latitude and by propagating LSM error into leakage corrections according to *Longuevergne et al.* [2010]. The estimated error might be slightly overestimated as variability

in the oceans may still contain geophysical signals. We convert the 10-day GRGS GRID solutions to a monthly time series by taking the average values in order to directly compare them with other GRACE solutions used in this study. Missing GRACE TWS data in CSR (June 2003) and GRGS (January, February, and June 2003) time-series products were imputed (i.e. infilling of missing values) using linear interpolation and monthly mean values.

2.2. Borehole hydrograph and groundwater storage

[9] We use weekly time-series records of borehole hydrographs from a subset of 236 shallow (mean well depth of 30 m below ground level, bgl) monitoring wells (see supplementary Figure S3 for borehole location) to assess changes in the groundwater storage over two periods (January 2003 – December 2007; January 1985 – December 2007). The first period represents recent changes in groundwater storage that are directly comparable to satellite observations under GRACE. The second period represents the longest period of groundwater storage changes for which observational records of high quality (mean missing record <4.3%) and density are available.

[10] The annual range (annual maxima – annual minima) in observed groundwater levels or hydraulic heads (Δh) in the regionally unconfined shallow aquifer (<100 m below ground level, bgl) in the Bengal Basin is translated into an equivalent groundwater depth (GWD) to derive *in situ* ΔGWS. Groundwater levels in shallow aquifers in Bangladesh reach the peak around September following rain-fed recharge through the monsoon season after their deepest levels observed towards the end of dry-season irrigation [*Shamsudduha et al.*, 2011]. Estimates of *in situ* ΔGWS are compared with GRACE-derived estimates according to equation 2 wherein $S_{gw}(t)$ is the trend in GWD and A is area of the same grid cells (n=27) within the Bengal Basin of Bangladesh over which time-series measurements of GRACE ΔTWS and ΔSMS data were collated.

$$\Delta GWS_t = \sum_{i=1}^{n} (S_{gw}(t) \times A_i) \qquad (2)$$

[11] S_{gw} is calculated at each monitoring location using specific yield value (S_y) and range in annual groundwater levels according to equation 3.

$$S_{gw} = \Delta h \times S_y \qquad (3)$$

[12] Similar to GRACE-derived ΔGWS estimates we apply both linear (August to October) and multiple linear trends to estimate *in situ* ΔGWS over the entire Bangladesh. Spatially distributed S_y values derive from 279 pumping test records [*Shamsudduha et al.*, 2011] are applied across Bangladesh (see supplementary Figure S4 for the location of pumping test and spatial distribution of S_y). The mean value of the estimated S_y in Bangladesh is 0.06 (range 0.01 to 0.2) with a standard deviation of 0.04. In light of uncertainty in values of S_y in Bangladesh [*Michael and Voss*, 2009], we compare this estimates derived from distributed S_y values with an upper-limit uniform value of 0.10; such a high S_y value (0.12) has similarly been applied regionally [*Rodell et al.*, 2009] where *in situ* derived values are absent.

2.3. Surface water storage and soil moisture

[13] ΔSWS used in our analysis refers primarily to flood-water loads and river storage as there are no irrigation dams or reservoirs in Bangladesh [*WARPO*, 2000]. The Bengal Basin in Bangladesh is, however, flood prone. Areas of up to one-third of the country (~48,000 km^2) are inundated by flood water each year and two-thirds of the country may be under water during extensive flood years [*Steckler et al.*, 2010]. We generate monthly time-series data of ΔSWS of a spatial resolution of 1°×1° using daily river-stage observations from 298 monitoring stations throughout Bangladesh (supplementary Figure S5 for seasonal variations

in the in-situ ΔSWS). This procedure involves: (i) conversion of daily river-stage records to mean monthly time series; (ii) interpolation (applying the Inverse Distance Weighting method using the GSTAT package in R programming language) of mean monthly river-level records (point data) over the entire Bangladesh on a regular grid size of 0.05°×0.05°; (iii) subtracting gridded surface-water level data from a resampled 300-m digital elevation model data on a regular grid size of 0.05°×0.05°, and (iv) aggregating interpolated values over a larger grid size of 1°×1° (n=27) over a period of January 2003 to December 2007 to generate mean monthly time-series of ΔSWS.

[14] Soil moisture is often the dominant contributor to ΔTWS variability in warm and temperate regions [*Rodell et al.*, 2009]. We apply monthly time-series soil moisture records from three simulations of the Global Land Data Assimilation System (GLDAS) [*Rodell et al.*, 2004]. Time series records of ΔSMS of a spatial resolution of 1°×1° derived from three LSMs such as CLM (v. 2) [*Dai et al.*, 2003], NOAH [*Ek et al.*, 2003], and VIC [*Liang et al.*, 2003]. The total depth of ΔSMS in CLM (10 layers), NOAH (4 layers), and VIC (3 layers) models are 3.4 m, 2.0 m, and 1.9 m respectively. In the absence of *in situ* ΔSMS data we use the ensemble mean of 3 LSMs-derived time-series data to represent ΔSMS in the Bengal Basin; a similar approach was used to estimate ΔGWS in northwestern India by *Rodell et al.* [2009] and central valley of California by *Famiglietti et al.* [2011]. None of these LSMs, however, includes groundwater storage [*Dai et al.*, 2003; *Rodell et al.*, 2004] or a specific module for surface water routing.

2.4. Disaggregation of GRACE ΔTWS

[15] Disaggregation of GRACE ΔTWS into GRACE-derived ΔGWS is carried out differently for GRID and SH products. For CSR GRID and GRGS GRID, we derive temporal changes in groundwater storage, ΔGWS, over the basin area (~138,000 km^2) in Bangladesh

by (i) extracting GRACE ΔTWS, ΔSMS, and ΔSWS time-series (January 2003 to December 2007) records for each 1°×1° grid cell (n=27; see supplementary Figure S6 for location), and (ii) averaging these time-series signals from all grids and applying the equation 1. Note that ΔSMS represents changes in soil moisture storage in all soil horizons and ΔSWS includes river and flood water storage. Changes in freshwater storage derived from ice and snow (ΔISS) are negligible in Bangladesh and not considered in this study. For CSR SH and GRGS SH, ΔGWS is resolved differently to reduce the propagation of uncertainties from bias and leakage variations on surface water and soil moisture. Equation (1) is applied to GRACE SH solutions to derive ΔGWS estimates. Bias (due to signal loss in internal water mass) and leakage (due to contribution from water mass outside of basin area) corrections are applied to GRACE-derived estimates of ΔGWS following the method described in *Longuevergne et al.*, [2010]. This method, however, requires information on ΔSMS and ΔSWS mass distribution in inside and outside of the basin area. The same filtering used for GRACE solutions (truncation at degree 60 and a 300 km Gaussian smoothing for CSR SH, truncation at degree 50 for GRGS SH) is applied to ΔSMS and ΔSWS before subtracting from the raw GRACE data (uncorrected for bias and leakage). Both spatial extent and mass variations in ΔSWS are known for the Bengal Basin. To account for temporal and spatial mass variability of ΔSWS outside of the Bengal Basin we use a global-scale model of surface water extent [*Papa et al.*, 2010].

[16] Linear and multiple linear trends were estimated from the basin-averaged GRACE derived ΔGWS. Linear trends (i.e. simple linear regression) in ΔGWS were calculated using data from the latter part of the wet season (August to October) of each year as these represent net changes in groundwater storage after the dry-season irrigation for high-yielding rice ("Boro") (Figure 1) cultivation and monsoon recharge have taken place [*Shamsudduha et al.*, 2011]. Estimates of linear trend in observed ΔGWS can be biased by the strong seasonality

(dry and wet season variations) present in the time-series records. To capture the highly seasonal structure in the ΔGWS signal, multiple linear trends (i.e. multiple linear regression) were calculated through the annual means of time series where, in addition to time (t), both sine $(\sin(2\pi t/T))$ and cosine $(\cos(2\pi t/T))$ functions of time are included as covariates; where T is the total number $(T = 12)$ of time unit (month) in the complete seasonal cycle of the time series. Other approaches to separate seasonality from trend and residual components in the time series (e.g., seasonal-trend decomposition based on filtering procedure) can be applied but accurate, bias-free (due to seasonality) decomposition will require longer time scales [*Cleveland et al.*, 1990; *Shamsudduha et al.*, 2009].

3. Results

[17] Figure 2 shows monthly time-series anomalies in all GRACE derived ΔTWS, simulated ΔSMS from 3 LSMs and their average, observed groundwater levels and river-stage levels, and average monthly rainfall in Bangladesh for the period of January 2003 to December 2007. ΔTWS signals derived from basin-averaged gridded GRACE products (CSR GRID, GRGS GRID) compare favorably (r >0.94, p-value >0.0001) with ΔTWS derived from GRACE SH data applying a basin function (CSR SH and GRGS SH) over the Bengal Basin in Bangladesh. Mean annual amplitudes in ΔTWS between 2003 and 2007 are 51 cm (CSR GRID), 52 cm (GRGS GRID), 49 cm (CSR SH) and 58 cm (GRGS SH). Although GRACE ΔTWS solutions are highly correlated, the amplitude is less well constrained and can vary by up to 15%. Variability among GRACE ΔTWS solutions (3.5 cm) is, however, within the estimated GRACE error (5 cm). The leakage correction error for the defined basin area is large and accounts for 3.5 cm of the estimated GRACE error.

[18] Substantial variations in magnitude are observed between ΔSMS signals derived from three LSMs (Figure 2c) and introduce considerable uncertainty in recovering ΔGWS from

ΔTWS. The mean seasonal amplitude in ΔSMS varies among the LSMs: 8 cm (CLM), 26 cm (NOAH) and 20 cm (VIC). At the outset of the monsoon season, ΔSWS rises quickly whereas ΔGWS responds more slowly with a lag of ~1 month to ΔSMS (Figure 2d). Overall, variations in individual water stores compare well with observed variability in monthly rainfall (Figure 2e). Figure 3 shows that the strong seasonality associated with the unimodal (monsoonal) distribution in annual rainfall is reflected in mean monthly time-series records of GRACE-derived ΔTWS, modeled ΔSMS, and *in situ* ΔSMS and ΔGWS.

[19] Estimates of ΔGWS over the period of 2003 to 2007 from observed borehole hydrographs, and all GRACE datasets are plotted in Fig 4. Changes in groundwater storage over the period of 2003 to 2007, estimated from GRACE data sets and borehole (*in situ*) hydrographs, are strongly correlated (Figure 4; Table 1). The highest Pearson correlation (r=0.93, p-value <0.0001) is observed between *in situ* ΔGWS and CSR SH derived ΔGWS time series. Time-series records of ΔGWS derived from GRGS SH are also strongly correlated (r=0.89, p-value <0.0001) to *in situ* ΔGWS in Bangladesh. Pearson correlations between *in situ* ΔGWS and GRGS (GRID and SH) derived ΔGWS are slightly lower than CSR datasets but cross-correlation analysis reveals that improved correlations (Table 1) are achieved by employing a time lag of 1 month in the time series (Table 1). The 1-month phase lag in time series of ΔGWS between GRGS-derived estimates and observed records in the highly-seasonal hydrological system of Bengal Basin can be attributed to the leakage correction in GRACE processing methodologies. Phases of ΔSMS and ΔSWS time series are in advance with respect to ΔGWS and a slight error in leakage correction can introduce such a time lag. Calculated uncertainty in GRACE-derived ΔGWS, represented in Figure 4, results from 16 possible estimates (4 GRACE solutions × 4 ΔSMS estimates derived from 3 LSMs and the mean of these).

[20] Linear trends and their standard errors in estimates of GRACE-derived and *in situ* ΔGWS averaged over the Bengal Basin in Bangladesh are summarized is Tables 2 and 3. Standard error in the simple linear regression is a measure of error (uncertainty) of an estimated coefficient (slope of trend line). Linear trends in wet-season (August – October) groundwater levels represent changes in ΔGWS as wet-season groundwater levels reflect groundwater storage after monsoonal recharge has taken place. The trend (January 2003 to December 2007) in ΔGWS based on wet-season groundwater levels is −0.52±0.30 km^3/yr (± standard error of linear trend estimate) using distributed S_y values; this rate of groundwater depletion increases to −1.06±0.59 km^3/yr if a uniform S_y value of 0.1 is applied. Multiple linear trends in annual means represent net changes in ΔGWS that can be influenced by declining groundwater levels or increased seasonality over time associated with increased groundwater-fed irrigation during the dry season. These *in situ* ΔGWS estimates therefore produce slightly higher rates of groundwater depletion (−0.85±0.17 to −1.61±0.32 km^3/yr). GRACE-derived estimates of ΔGWS losses using a simulated mean ΔSMS range from −0.44±1.24 to −2.04±0.79 km^3/yr for wet-season trends and −0.52±0.50 to −2.83±0.42 km^3/yr based on trends in annual means.

[21] Short-term changes in ΔGWS, estimated over the period for which GRACE data are available, are highly sensitive to the length of the time series. For example, trends in ΔGWS estimated for a shorter (2003 to 2006) period are nearly twice that calculated for the period of 2003 to 2007 (Tables 2 and 3). Long-term (1985 to 2007) trends derived from *in situ* ΔGWS rates are considerably lower (−0.21±0.03 to −0.23±0.02 km^3/yr) than those calculated over the period of GRACE observations. The estimation of *in situ* ΔGWS from borehole hydrographs enables the identification of areas of rising and falling groundwater storage over both short (2003 to 2007) and long (1985 to 2007) periods of observation (Figure 5). Over both periods, there are decreasing trends in ΔGWS in central and northwestern parts of

Bangladesh and rising trends in southwestern and coastal regions. Relative to long term terms, trends in recent *in situ* ΔGWS have reversed in northern areas and intensified in central and northwestern regions.

4. Discussion

[22] Intra-annual (seasonal) variations and inter-annual trends in ΔGWS derived from both gridded GRACE and GRACE SH datasets in the tropical, humid Bengal Basin compare very well with estimates of *in situ* ΔGWS derived from borehole observations (Table 1, Figure 4). Similarity in the signals of *in situ* and GRACE time-series records of ΔGWS is characterized using their correlation coefficients, centered root mean square (RMS) difference and amplitude of variations (represented by standard deviations) and represented graphically in Figure 6 [*Taylor*, 2001]. High correlation coefficients (r >0.85, p-value <0.0001) and low RMS error (<5 cm) suggest that all CSR GRACE datasets (both gridded and SH) closely match *in situ* observations among the GRACE-derived ΔGWS estimates. There are, however, a number of sources of uncertainty and underlying assumptions that are inherent to both techniques. Estimation of *in situ* ΔGWS assumes: (1) trends in groundwater levels do not result from inhomogeneities in observation records; and (2) values of S_y used to convert groundwater levels to ΔGWS, are representative of the monitored aquifer. Estimation of GRACE-derived ΔGWS assumes: (1) an accurate estimate of ΔSMS contribution from LSMs and ΔSWS from observations to recover ΔGWS; and (2) water storage is well described by LSMs inside the area of interest and in the surrounding area to estimate bias and leakage effects. The second point is not obvious in a highly seasonal basin featuring large spatial and temporal variability in (water) mass. For example, variability among LSMs is not substantially reduced following the application of filters to GRACE data; variability expressed as a standard deviation that is 6.5 cm for raw LSM data, becomes 4.0 cm and 5.1

cm under CSR-like and GRGS-like filters respectively. GRACE solutions consequently suffer from the propagation of uncertain storage variability (different for CSR and GRGS solutions) surrounding their region of interest. Indeed, this problem may explain the noted differences in seasonal amplitudes and leads to larger RMS error in ΔGWS recovery (6 cm) relative to the amplitude of seasonal variations (20 cm).

[23] Another difficulty in trend estimation in this region relates to leakage of glacier melt from the Himalayas [*Matsuo and Heki*, 2010]. Forward modeling indicates that leakage of glacial mass changes (+2%) from the Himalayas into the Bengal Basin region for the CSR solution whereas for the GRGS solution it is the reverse (-1%). The difference in sign may be explained by the hard truncation for the GRGS solution. Although the value is small, a large glacier mass loss of ~50 cm/yr [*Matsuo and Heki*, 2010; *Bolch et al.*, 2011] induces mass changes of +1.38 km^3/yr for CSR GRACE data and −0.69 km^3/yr for GRGS GRACE data into the Bengal Basin. This explains why estimated trends in ΔGWS derived from GRGS (SH and GRID) data are systematically smaller than those for CSR (SH and GRID) data.

[24] Uncertainty in simulated ΔSMS associated with the choice of LSM (GLDAS) for GRACE disaggregation also contributes substantially (standard deviations from CLM, NOAH and VIC models are 3, 11 and 8 cm respectively) to overall calculated uncertainty in ΔGWS. Seasonal variability in simulated ΔSMS is observed in LSMs derived time-series datasets (supplementary Figure S7). NOAH model derived ΔSMS represents the greatest seasonal variability (i.e. annual amplitude) whereas CLM-derived ΔSMS shows the least seasonal variation. Our estimated ΔSMS ($\Delta TWS - \Delta GWS - \Delta SWS$) shows strong correlations (r=0.83, p-value <0.0001 for CSR GRID; r=0.89, p-value <0.0001 for CSR SH) with the average ΔSMS derived from 3 LSMs. Individually, VIC model derived ΔSMS compare well with the estimated ΔSMS time-series data. It is also unclear whether LSMs capture large inter-annual variability in the Asian monsoon associated with climatic teleconnections such

as ENSO and IOD. Other uncertainties in GRACE-derived estimate of ΔGWS associated with the use of simulated (GLDAS LSMs) ΔSMS can arise from (1) under-representation of ΔSMS in areas of thick unsaturated zone, and (2) over-representation of ΔSMS in areas of very shallow groundwater table and substantial surface water storage. In the latter case, simulated ΔSMS may include parts of shallow groundwater and surface water storage due to poor compartmentalization of individual terrestrial water stores [*Gulden et al.*, 2007]. In the Bengal Basin, areas featuring a deep unsaturated soil zone are minimal (present only in thick clay-covered Pleistocene terrace areas) as groundwater levels in Bangladesh predominantly occur at very shallow depths (see supplementary Figures S1 and S2). In this study, the use of an average value of simulated ΔSMS from 3 LSMs, however, minimizes the uncertainty in estimation of ΔGWS using GRACE satellite measurements.

[25] We demonstrate that resolving trends in ΔGWS is problematic over short (e.g. 4 to 5 year) periods in a highly seasonal basin where seasonality in water storage is greater than the trend. Seasonality (i.e. annual amplitude) in ΔTWS in the Bengal Basin generally results from monsoonal flooding during the wet season and intensive groundwater abstraction during the dry-season. The trend in estimated ΔGWS for a 5-year period (2003 to 2007) is approximately half of that estimated from 2003 to 2006. Additionally, estimation of trend in ΔGWS in the Bengal Basin can be problematic due to the presence of strong seasonality in the dataset. We demonstrate that the strong seasonality in ΔGWS can however be captured well in multiple linear regression by using additional covariates (e.g. sine and cosine function of time) and error in trend estimates can be minimized (Tables 2 and 3).

[26] Critical to our estimation of ΔGWS from GRACE data in the Bengal Basin is the robust resolution of ΔSWS from *in situ* observations as ΔSWS accounts for 22% of the total variability in GRACE-derived ΔTWS. This contribution although very critical in humid tropics [*Frappart et al.*, 2011] is often ignored in flood-prone regions around the world

[*Swenson et al.*, 2006; *Rodell et al.*, 2007; *Tiwari et al.*, 2009] as flood water is mostly unregulated or its effect on ΔTWS is assumed to be negligible relative to ΔSMS.

[27] Estimated rates of groundwater depletion in the Bengal Basin (−0.52±0.30 to −1.61±0.32 km^3/yr equivalent to −0.34 to −1.14 cm/yr) are substantially lower than those recently estimated elsewhere on the Indian sub-continent by *Rodell et al.* [2009] in semi-arid, northwestern India (−4.0 cm/yr), and *Tiwari et al.* [2009] for Bangladesh, Nepal and West Bengal (India), their "zone D" (−2.5 cm/yr). More recently, another study [*Llovel et al.*, 2010] has reported trends in ΔTWS (August 2002 to July 2009) of −1.1 cm/yr and −1.5 cm/yr over the River Ganges and Brahmaputra Basins respectively. Each of these studies attributes groundwater depletion to intensive groundwater-fed irrigation. In the Bengal Basin, more rapid groundwater storage depletion estimated for the period 2003 to 2007, relative to 1985 to 2007, is linked to substantial increases in groundwater abstraction for irrigation and urban water supplies [*Hoque et al.*, 2007; *Shamsudduha et al.*, 2009; *Shamsudduha et al.*, 2011]. *In situ* measurements show further that groundwater depletion primarily occurs in central (Dhaka city) and northwestern Barind Tract areas of Bangladesh where a low-permeability surficial deposit (Madhupur Clay Formation; see supplementary Figure S4 and S8 for hydraulic properties of the shallow aquifer in Bangladesh) of variable thickness (6 to 40 m) inhibits direct rainfall-fed recharge [*Shamsudduha et al.*, 2011].

[28] A curious finding is the more favorable comparison that is observed between wet-season trends in ΔGWS derived from GRACE (−0.44±1.24 to −2.04±0.79 km^3/yr) and *in situ* observations using a high, uniform estimate (0.1) of S_y (−1.06±0.59 to −1.61±0.32 km^3/yr) rather than a spatially distributed value (mean: 0.06±0.04) of S_y (−0.52±0.30 to −0.85±0.17 km^3/yr) derived from pumping tests. In the large Mississippi Basin, *Rodell et al.* [2007] stress the importance of applying representative, distributed storage coefficients but, as recognized by a recent study [*Sun et al.*, 2010], the determination of S_y is challenging. S_y values derived

from pumping tests can be biased toward low values in two ways. First, elastic storage often dominates short pumping tests where confined or semi-confined exist locally and water-table drainage has insufficient time to respond. Second, *in situ* estimates of S_y, that sample an area of <0.5 km^2 but are scaled up to a 1°×1° grid cell (used in our analysis of *in situ* ΔGWS), do not represent the considerable variability in S_y that naturally exists in alluvial aquifers. The influence of low S_y values may be exaggerated at regional scales as abstraction and resultant groundwater depletion are biased to areas of higher S_y. Our deductions highlight the current but under-explored uncertainty associated with the selection of storage coefficients to reconcile ΔGWS from GRACE, as an equivalent groundwater depth, with *in situ* monitoring observations from borehole hydrographs.

5. Conclusions

[29] In a highly seasonal hydrological system in the humid tropics, the Bengal Basin, we show that GRACE satellite measurements closely trace recent (2003 to 2007) intra-annual (seasonal) and inter-annual variations in groundwater storage (ΔGWS) indicated by *in situ*, ground-based observations (borehole hydrographs). Critical to this analysis is the resolution of ΔGWS from total water storage (ΔTWS) derived from GRACE using (1) changes in observed surface water storage (ΔSWS) derived from river stage records monitored at 298 gauging stations; and (2) changes in simulated soil moisture storage (ΔSMS) using 3 Land Surface Models (LSMs) (CLM, NOAH, and VIC). GRACE-derived ΔTWS in the Bengal Basin from 2003 to 2007 is explained well by changes in surface water storage (ΔSWS) (22%), changes in soil moisture storage (ΔSMS) (33%), and ΔGWS (44%). Groundwater depletion in the Bengal Basin estimated from *in situ* observations using a distributed specific yield (S_y) ranges from −0.52±0.30 km^3/yr (wet season trends) to −0.85±0.17 km^3/yr (trend in annual means). These estimates are highly comparable (within error) to the range in estimates, −0.44±1.24 to −2.04±0.79 km^3/yr (wet-season trends) and −0.52±0.50 to −2.83±0.42 km^3/yr (trends in annual means), derived from different GRACE datasets (gridded and spherical harmonic (SH) products of CSR and GRGS). Of the 4 GRACE solutions, CSR SH derived ΔGWS shows the highest correlation (r=0.93, p-value >0.0001) and the lowest (<4.0 cm) RMS error with *in situ* ΔGWS estimates with distributed specific yield. It remains unclear whether the small discrepancy between *in situ* and GRACE satellite estimates derives from uncertainties in resolving GRACE ΔGWS from ΔTWS or the representivity of storage coefficients derived from *in situ* pumping tests. Estimates of the linear trend in ΔGWS are highly dependent upon the length of the time series (e.g. 2003-2006 vs. 2003-2007). Calculated trends are also strongly influenced by the annual variability in the amplitude; errors can arise from residual inter-annual variations once the seasonal component is removed from the time series. Long-term (1985 to 2007) trends in observed ΔGWS (−0.21±0.03 to −0.23±0.02 km^3/yr) are considerably lower than recent (2003 to 2007) trends and indicate higher rates of groundwater depletion as a result of increased groundwater abstraction for irrigation and urban water supplies.

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Figure Captions:

Figure 1. Map shows areas of dry-season Boro rice cultivation in 2007−2008 in Bangladesh (data from Bangladesh Space Research and Remote Sensing Organization) and percentage of land (graduated circles) in each of the country's 64 districts irrigated with groundwater using shallow and deep tubewells. Map also shows digital elevation (gray shades), river channels (blue polylines), district level boundaries (thin gray lines), and the international boundary (solid black line).

Figure 2. Monthly time series anomaly of water stores for the period of January 2003 to December 2007: (**a**) averaged gridded GRACE products (CSR GRID and GRGS GRID); (**b**) spherical harmonics GRACE products with measurement error (CSR SH and GRGS SH) extracted over the Bengal Basin of Bangladesh using a basin function; (**c**) 3 simulated soil moistures (CLM, NOAH, and VIC) and their average value (AvgSMS) derived from GLDAS Land Surface Models (LSMs); (**d**) monthly anomalies in groundwater storage averaged from a total of 236 monitoring locations and surface water storage averaged from a total of 298 gauging stations; and (**e**) mean monthly rainfall averaged from a total of 250 BWDB stations (2003 to 2006) and a total of 15 weather stations managed by Bangladesh Meteorology Department. Total annual rainfall (mm) for each year from 2003 to 2007 is provided.

Figure 3. Mean (2003-2007) monthly GRACE TWS (both gridded and spherical harmonics GRACE products), average LSM-derived soil moisture storage (ΔSMS), observed surface water storage (ΔSWS), borehole-derived groundwater storage (ΔGWS), and rainfall in Bangladesh. Strong seasonality with variable magnitudes in terrestrial water stores in the Bengal Basin (soil moisture, surface water, and groundwater storage) results from seasonal (monsoonal) rainfall. Peak level of ΔGWS lags the peak level of ΔSWS by approximately 1 month where correlation is the highest (r=0.93, p-value <0.0001); the peak level of ΔGWS occurs almost at the same time as the ΔSMS (r=0.91, p-value <0.0001).

Figure 4. Comparison of monthly time-series anomaly (cm) of groundwater storage (ΔGWS) in Bangladesh derived from borehole hydrograph with GRACE derived ΔGWS estimates for the period of January 2003 to December 2007. Time series of ΔGWS derived from borehole hydrograph with distributed specific yield (GWS S_y = distributed; blue line) and a uniform

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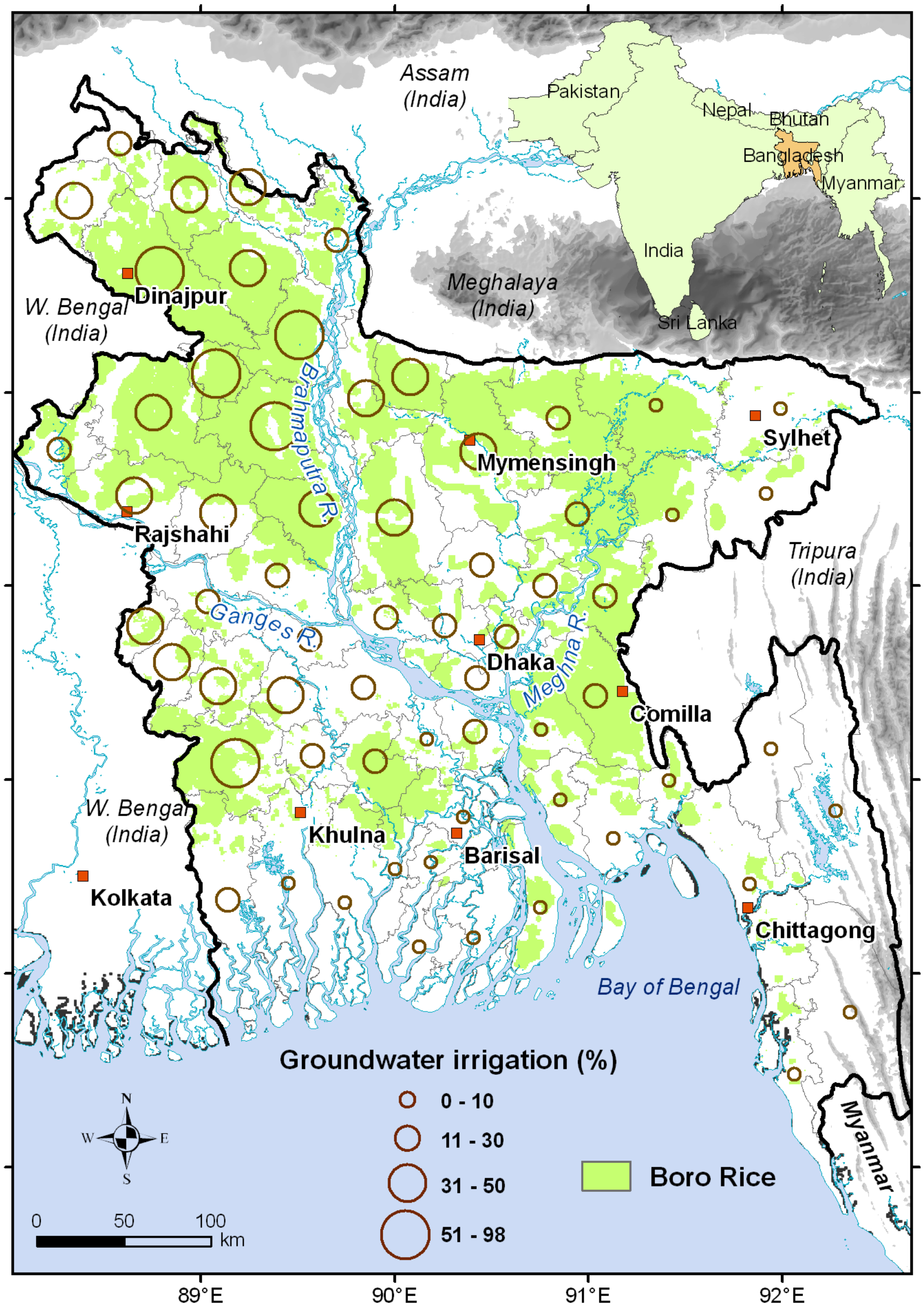
Figure 5. Groundwater storage changes (ΔGWS) in the Bengal Basin of Bangladesh expressed as trends (cm/year) in equivalent groundwater depth (GWD) derived from borehole hydrographs. Panels (**a**) and (**b**) show trend estimates in GWD from linear (through wet-season values) and multiple linear (through entire time series) respectively for the period of 2007 to 2007; panels (**c**) and (**d**) show linear and multiple linear trends in GWD for a longer period (1985 to 2007). Areas of recent declines in ΔGWS are highlighted in top two panels.

Figure 6. A Taylor diagram [*Taylor*, 2001] displaying pattern statistics between *in situ* ΔGWS with distributed specific yield (S_y = dist) and 6 models of GRACE-derived ΔGWS and 2 *in situ* ΔGWS models with S_y = 0.1 and the national mean (0.06) value. The radial distance (dashed blue lines) from the origin is proportional to the standard deviation of ΔGWS estimates. The centered root mean square (RMS) difference between the modeled (colored circles) and observed field (black square) is proportional to their distance apart (in the same units as the standard deviation). The correlation between the two datasets is given by the position of the modeled observation (dashed black lines). In the legend, CSRSH GWS (corr) and GRGSSH GWS (corr) denote estimates are corrected for leakage and bias using methods described in *Longuevergne et al.* [2010]. CSRSH GWS (std) and GRGSSH GWS (std) denote estimates derived using basin-averaged time series data without bias/leakage corrections. Based on the diagram it is evident that CSR GRACE datasets compare well *in situ* ΔGWS estimate whereas all estimated values range between *in situ* ΔGWS estimates with S_y = 0.1 and 0.06 values.



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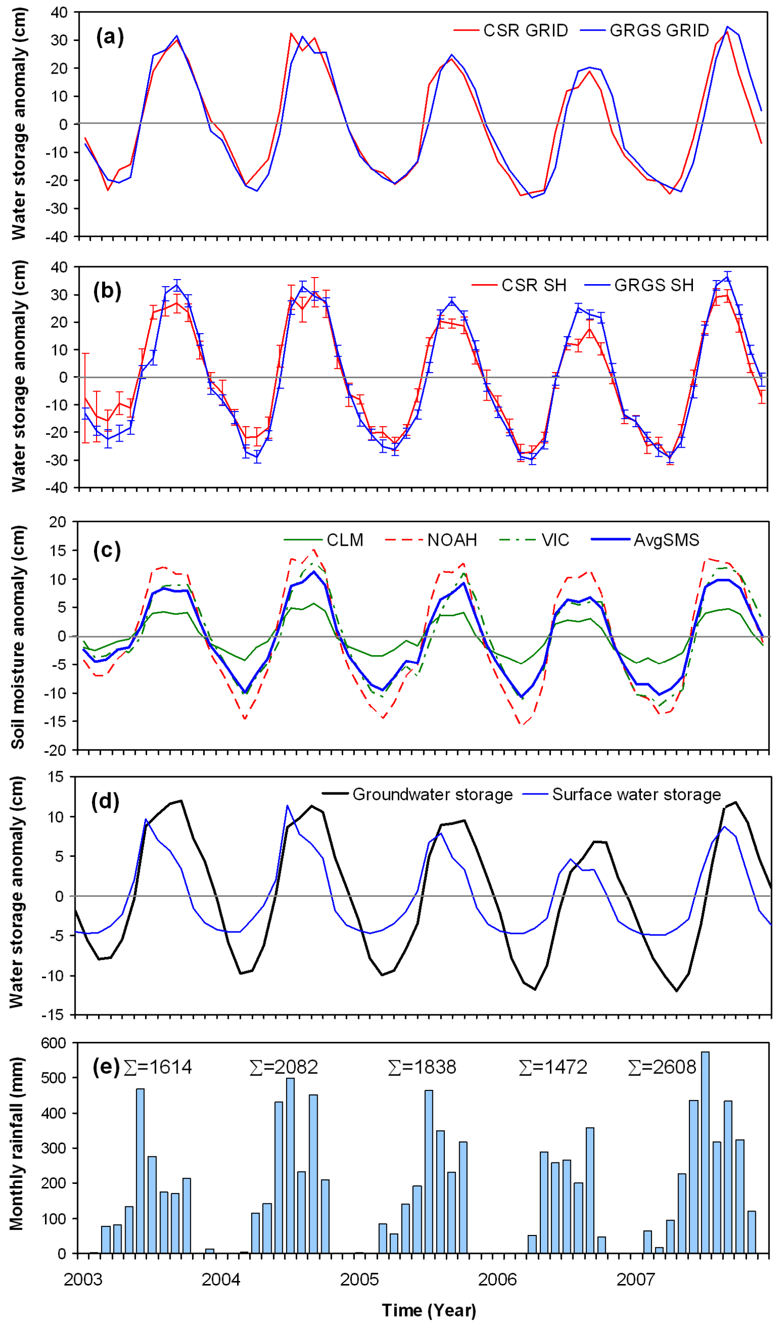

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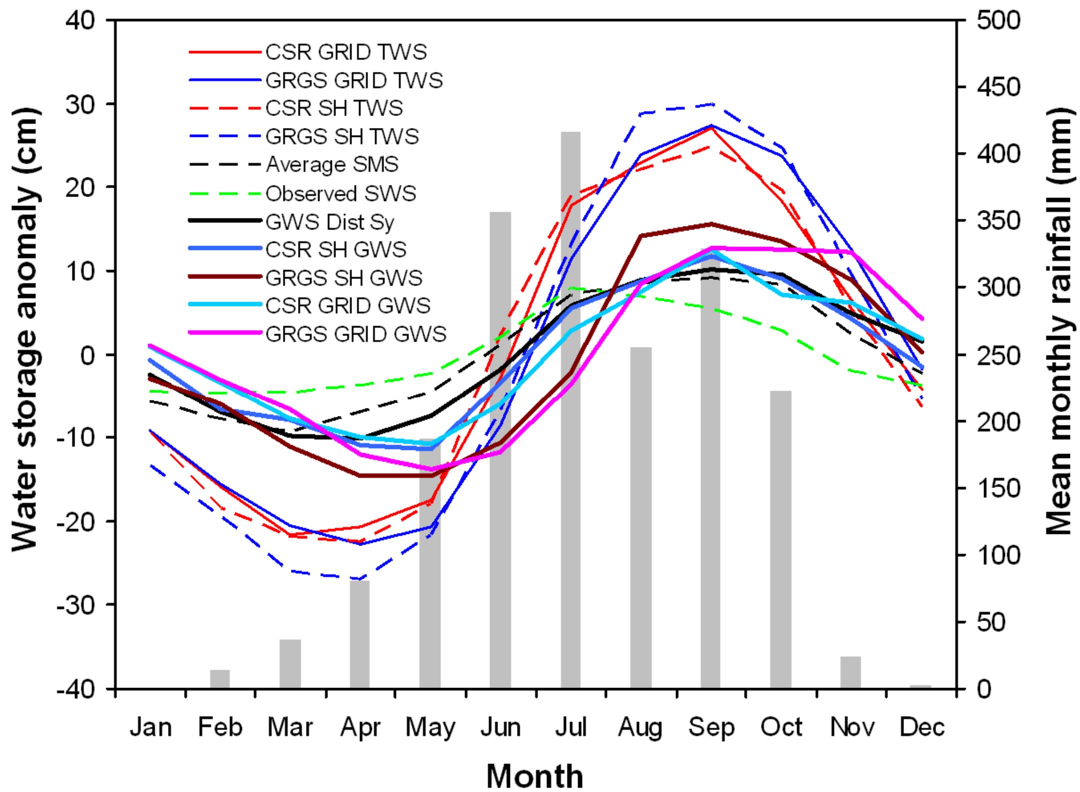

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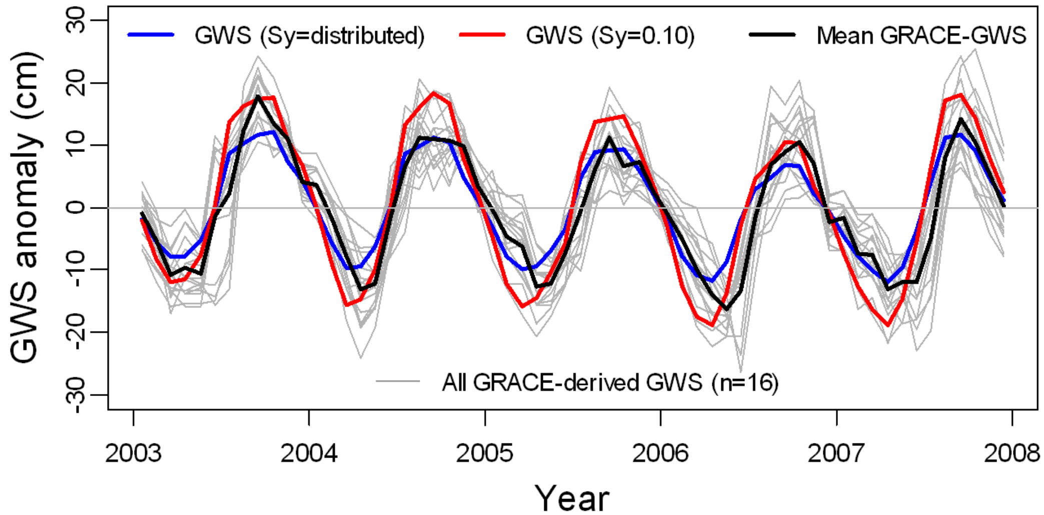

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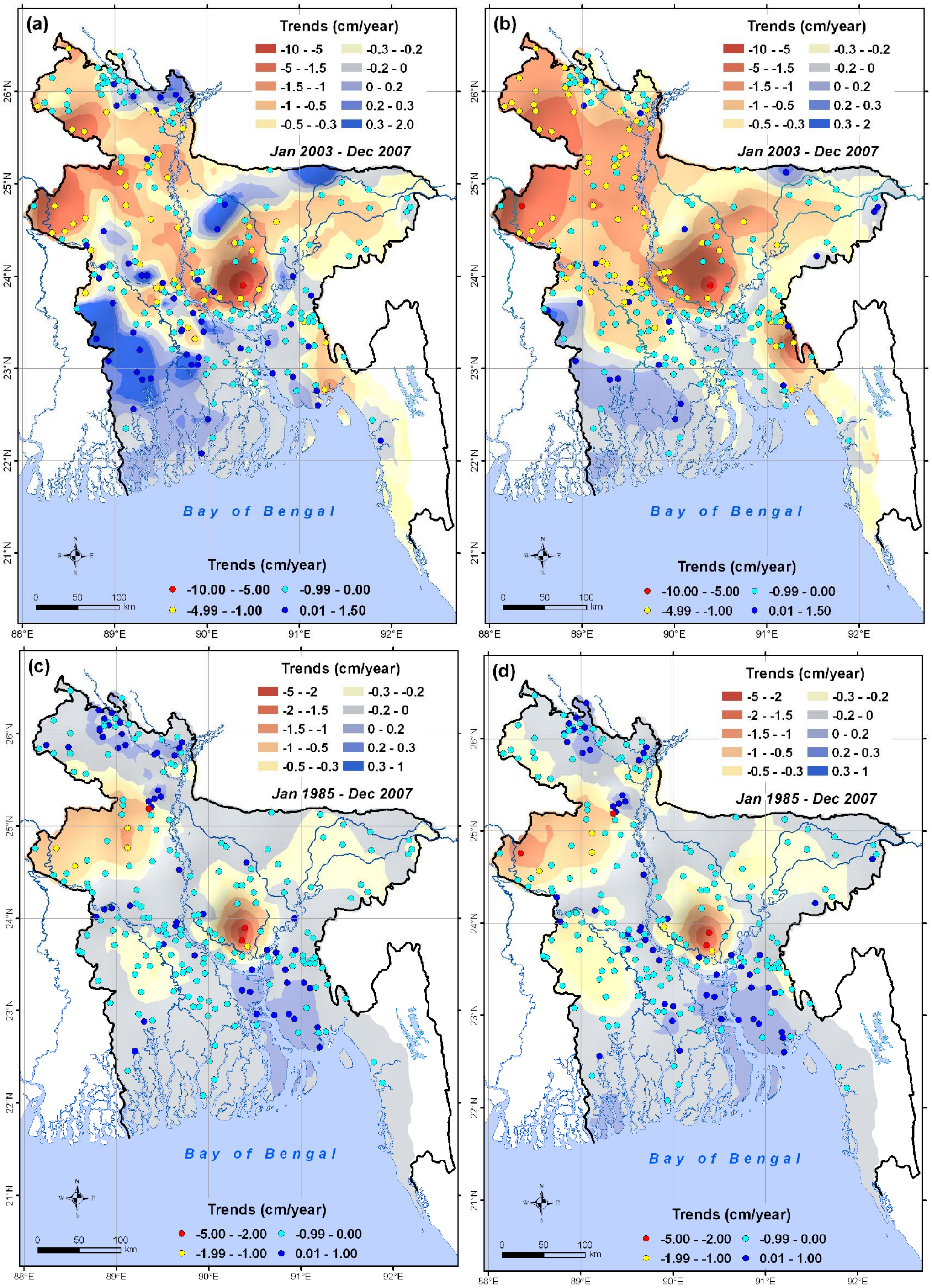

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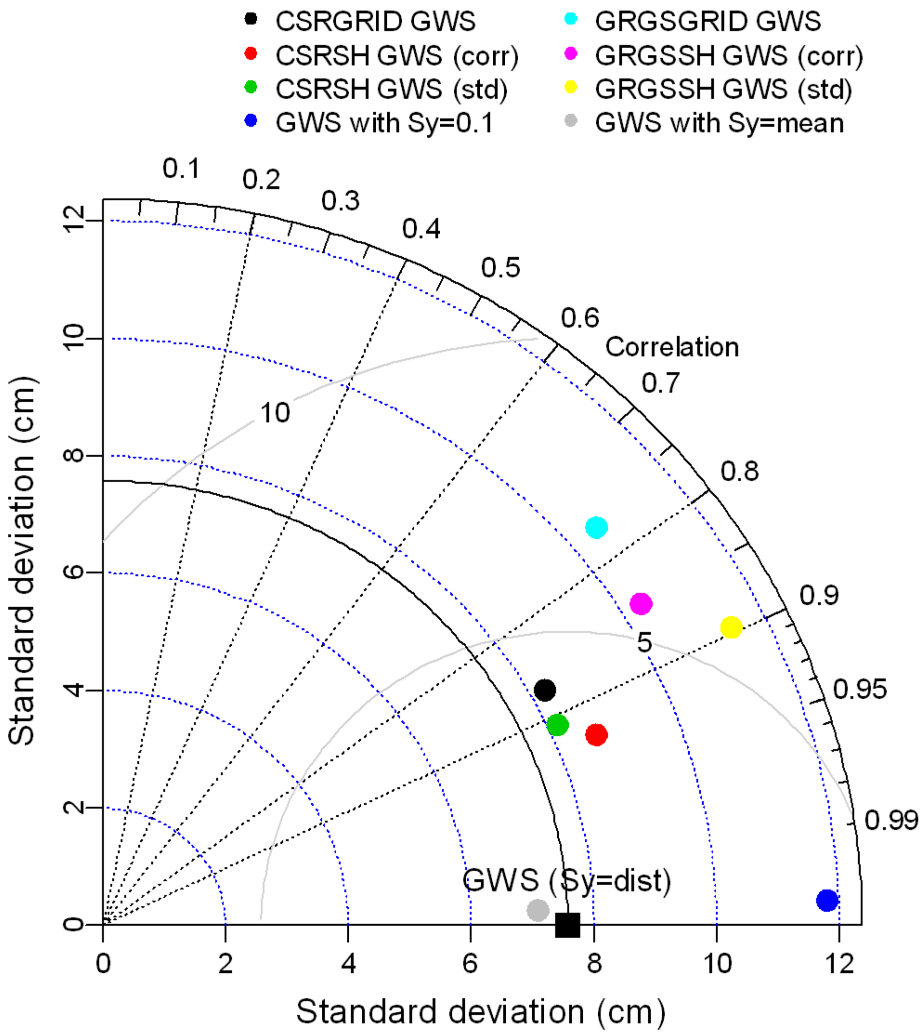

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